LOW LOSS DESIGN OF THE LINAC AND ACCUMULATOR RING FOR THE SPALLATION NEUTRON SOURCE[*]

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Introduction

The Spallation Neutron Source (SNS) is a second generation pulsed neutron source and is presently in the fourth year of a seven-year construction cycle at Oak Ridge National Laboratory. A collaboration of six national laboratories (ANL, BNL, LANL, LBNL, ORNL, TJNAF) is responsible for the design and construction of the various subsystems [1]. The operation of the facility will begin in 2006 and deliver a 1.0 GeV, 1.4 MW proton beam with pulse length of 650 nanosecond at a repetition rate of 60 Hz, on a liquid mercury target. It consists of an RF volume H^- source of 50 mA peak current at 6% duty; an all electrostatic Low-Energy Beam Transport (LEBT) which also serves as a first stage beam chopper with $\pm$ 25 ns rise/fall time; a 402.5 MHz, 4-vane Radio-Frequency Quadrupole (RFQ) for acceleration up to 2.5 MeV; a Medium Energy Beam Transport (MEBT) housing a second stage chopper ($<\pm$ 10ns rise/fall), an adjustable beam halo scraper, and diagnostics devices; a 6-tank Drift Tube Linac (DTL) with permanent magnet quadrupoles up to 87 MeV; an 805 MHz, 4-module, Side Coupled Cavity Linac (CCL) up to 186 MeV; an 805 MHz, superconducting RF (SRF) linac with eleven medium beta (β=0.61) cryo-modules and twelve high beta (β=0.81) cryo-modules accelerating the beam to the full energy; a High Energy Beam transport (HEBT) for diagnostics, transverse and longitudinal collimation, energy correction, painting and matching; an accumulator ring compressing the 1 GeV, 1 ms pulse to 650 ns for delivery onto the target through a Ring to Target Beam Transport (RTBT) with transverse collimators. The major parameters are shown in Table I. Specific low loss design features will be discussed in Section 2, and beam losses in Section 3.

Table I: Spallation Neutron Source major parameters

Beam energy on target (MeV)	1000	Ring space charge tune spread	0.15
Beam Current on target (mA)	1.4	SRF cryo-module number	11+12
Beam power on Target (MW)	1.4	SRF cavity number	33+48
Pulse repetition rate (Hz)	60	Peak field E_p (β=0.61) (MV/m)	27.5
Proton Pulse width (ns)	695	Peak field E_p (β=0.81) (MV/m)	35
Proton per pulse	1.4×10^{14}	High β sc linac output energy (MeV)	1000
Beam size at target (cm x cm)	20 x 7	Med β sc linac output energy (MeV)	397
Ring circumference (m)	248	CCL output energy (MeV)	186
Ring RF frequency (MHz)	1.058	DTL output energy (MeV)	87
Ring Injection time (ms)	1.0	RFQ output Energy (MeV)	2.5
Ring beam extraction gap (ns)	250	LEBT output energy (MeV)	0.065

(2) Low Loss Design

The most stringent requirement for the SNS accelerator complex is to allow hands-on maintenance. This requirement implies that the allowable residual radiation is below 100 mrem/hour at 30 cm from the beam vacuum pipe four hours after the shut down, after one hundred days of normal operation. Based on operational experiences, it has been shown that this limit corresponds to an average of 1-2 Watts of lost beam power per tunnel-meter [2]. This loss level will be achieved through specific design features throughout the machine, except in specific areas. These areas have been identified and correspond to collimation sections and beam dumps where a large amount of beam loss is foreseen. Beam losses in these areas are categorized as controlled beam loss. We will discuss the specific built in design features to prevent localized losses and reduce overall beam losses in following subsections.

2.1 Front End: An rf-excited volume H^- ion source was chosen for its low emittance and successful operation at the SCC [3]. Since the beam from source is round and the RFQ needs a round beam, the natural choice of lattice elements are circular lenses, either electrostatic or magnetic. To avoid losses at ring extraction, a gap of 250 ns (32%of the ring pulse length) with cleanness better than 10^{-4} in the beam pulse train of 1 ms is needed. It is best to create this gap at as low an energy as possible to reduce chopped beam power. Beam chopping is accomplished in two stages - most of the chopping (27.7%) will be done in LEBT to reduce chopped beam power, and the remaining 4.35% beam chopping will be obtained MEBT to

achieve a cleanness of 10^{-4}. BNL experience [4] has shown that a fast chopper in a magnetic LEBT does not chop the beam properly because of space charge effects and H⁻ beam neutralization. These problems can be avoided if one uses an electrostatic LEBT [5]. In this all electrostatic LEBT [6], one of the electrodes in the pseudo einzel lens is divide into four segment and a voltage rotating between the four segments is used to defect the beam on to the RFQ face plate, achieving 20 ns rise/fall times and beam removal of 27.7%[7]. This LEBT has sufficient degrees of freedom (knobs) to match into the RFQ. The RFQ physics design [8] is very much conventional, except the shaper section is unusually long to reduce the longitudinal emittance. The transmission through RFQ is more than 80% and all the losses are in the buncher section. Generally the MEBT design is the result of many compromises [9] because of the different demands on this section, and is a major source of emittance growth and halo generation. The lattice in the MEBT is neither FODO nor FFODDO, which are the lattices of the RFQ and the DTL respectively. At both ends of the MEBT, the lattice is FODO, and a couple of triplets are used in the middle to create the long spaces for the chopper and anti-chopper. The MEBT has 18 quadrupoles and four buncher cavities, chopper and anti-chopper, in a length of 3.7 meters [10]. The rise/fall time of the chopper is 10 ns, so 4 micro-bunches will be partially chopped and might be lost in the downstream linac. An anti-chopper is used for the first time to compensate the partially kicked beam which occurs during the rise/fall time of the chopper. The remaining 4.3% beam is chopped and collected on a molybdenum beam target. The MEBT also houses x and y beam scrappers to stop halo particles [11].

2.2 Warm Linac: The warm linac [12] consists of 6 DTL tanks up 87 MeV and 4 CCL modules in the configuration of 12 cavities per module and 8 cells per cavity, up to 186 MeV. Structure resonances are avoided by limiting the restoring forces. The envelope instability occurs at a zero current phase advance of 90 degrees, and the transverse phase advance in the DTL and CCL are below 80 and 85 degrees, respectively. The longitudinal phase advance in the DTL and CCL are below 75 and 50 degrees. The transverse wave number k_{0t} is made continuous by choosing a lattice period of 6 $\beta\lambda$ in the DTL and 13 $\beta\lambda$ in the CCL. Similarly k_{0l} is also made continuous in the DTL and CCL, by ramping the E_0 and ϕ_s in the first tanks of the DTL. Minimizing rms mismatch controls the beam oscillations. One of the potential sources of longitudinal mismatch comes from missing gaps between DTL tanks. These missing gaps can be compensated by adjusting ϕ_s in the adjacent gaps [13]. The main sources of mismatch are from the MEBT-DTl transition, and the DTL-CCL transition. The space charge tune depression in the DTL and CCL are above 0.5 to avoid instabilities.

Space charge coupling can cause energy transfer between phase planes. Anisotropy ($T=\sigma_l/\sigma_t * \epsilon_l/\epsilon_t$) is assumed to be the driving mechanism for this energy transfer. The time constant for this effect is typically long ($>10\tau_{plasma}$) and depends on (a) longitudinal to transverse emittance ratio, (b) tune depression and (c) tune ratio. There are internal resonance bands at integer values of σ_l/σ_t. The SNS warm linac design does not cross a structure resonance, but does cross the first internal resonance twice at the MEBT-DTL and CCL-SRF matching points. This does not linger more than 50 ns or 2 τ_{plasma} and the beam is equipartitioned at these crossing points [14].

2.3 Superconducting RF linac (SRF): The SRF linac [15] provides a higher accelerating field (11-16 MV/m), one encounters less beam loss and halo scraping due to its larger aperture and better vacuum, is immune to one cavity/klystron failure, and is expected to have higher reliability and availability in comparison to a warm linac (CCL). On the other hand, it will be the first SRF proton linac for such high energy, with new uncertainties of ion beam ($\beta < 1$) under Lorentz detuning, and microphonics.

The SRF linac has two sections distinguished by their "geometric β". The medium beta ($\beta=0.61$) section has 33 6-cell cavities with a peak surface field of 27.5 (±2.5) MV/m and the high beta ($\beta=0.81$) section has 48 6-cell electro-polished cavities with peak surface fields of 35.0 (+2.5/ -7.5) MV/m. Each cavity will be driven by its own klystron, to have independent control over phase and amplitude, which is necessary for an ion beam ($\beta < 1$) undergoing Lorentz detuning, microphonics, beam transients, and injection energy offset. Like the warm linac k_{0l} & k_{0t} are kept continuous at the cost of lower longitudinal acceptance. Again, phase and quad laws are chosen to avoid structure and parametric resonances and reduce risk of coherent resonances for emittance growth [12].

2.4 High energy beam transfer line: The HEBT [16] is about 180 meters long, and not only carries the H⁻ ions to the ring from the linac, but also optically matches the linac and ring, corrects energy jitter from the linac, increases the energy spread of the beam to avoid beam instability in the ring, cleans transverse and longitudinal halo coming from the linac, characterizes the beam from the linac, and protects the ring from

fault conditions. This line has two new features: (a) it has transverse and longitudinal halo scrapers followed by absorber collimators [17]. The scrapers are the thick carbon charge exchange foils to convert halo H^- ions to protons, which find themselves in the H^- lattice and therefore defocused and dump at the absorber collimators. This beam loss is considered as controlled beam loss and reduces uncontrolled beam loss. (b) There are two RF cavities, the energy corrector and energy spreader cavities [18]. The energy corrector cavity operates at the linac frequency and compensates energy jitter in the incoming linac beam. The energy spreader operate at a phase modulated mode of the linac frequency, and provides the energy spread required for beam stability in the ring.

2.5 Accumulator ring: The 248 m long four-fold symmetric lattice contains four achromatic arcs (4 FODO cells with 90° horizontal phase advance) and four dispersion free straight sections, each housing injection, collimation, extraction and RF [19]. The dispersion free straight sections make the following possible (a) Injection: transverse and longitudinal phase spaces can be painted independently [20], (b) RF: avoids coupling in transverse and longitudinal planes, and (c) collimator: with a flexible phase advance improves collimator efficiency [21]. To keep the losses below 1 W/m, the accumulator ring is designed with the following features. (1) The magnetic fields in the injection area are chosen to prevent premature H^- and H^0 stripping [22]. (2) The transverse phase space is painted with so called "correlated painting" in quasi-uniform distribution (200 π mm mrad) to keep the space charge tune shift below 0.15 and to fulfill demanding target requirements with a specific distribution [23]. The average number of foil traversals were minimized to prevent excessive foil temperature, multiple and nuclear scattering in the foil and Landau energy tail [24]. (3) The ring transverse acceptance will be 480 π mm mrad, allowing the beam tail and beam halo to be cleaned by the collimator system (scraper at 260 and fixed collimator at 300 π mm mrad) with high efficiency before hitting the rest of the ring. (4) Beam ($\Delta p/p = \pm 1\%$) fills only 70% of the momentum acceptance of a stationary rf bucket and vacuum chambers are designed for a full momentum aperture of $\Delta p/p = \pm 2\%$. (5) All the ring magnets have achieved field quality $\Delta B/B < 10^{-4}$ at full aperture for 1.0 GeV operation and are sorted for 1.3 GeV operation [33]. (6) To avoid all instabilities, vacuum chambers are coated with Ni [34], chamber steps are tapered, and an electron catcher in the injection area is provided. (7) To clean the extraction beam gap, the accumulator design includes fast vertical kickers to kick any beam in the extraction gap into the collimation system [25].

2.6 Ring to Target Beam Transport (RTBT): A 150 meter long transport line connects the ring to target and houses two transverse collimators and a beam spreader system to provide the desired beam foot print at the target. RTBT is immune to a single kicker failure and the ratio of acceptance (480 π mm mrad) to rms emittance (36 π mm mrad) is more than 10 [26].

2.7 Beam Dumps: There are three beam dumps in SNS accelerator complex [27]: linac output, ring injection and ring extraction. Linac and extraction dumps are designed for 7.5 kW of beam power and will be used for beam tuning purposes. The linac dump will also collect the H^0 coming from stripping throughout the entire linac, estimated at about 20 watts. The injection dump is designed for 200 kW of beam power, and will collect H^- ions which have missed the injection foil, and partially stripped H^0 from the injection foil.

(3) Beam Losses
3.1 Controlled Beam Losses: As described in Section 2, the localized beam losses in specific areas which are designed to handle larger amounts of beam losses are categorized as controlled beam loss. The following losses are identified as controlled beam losses: (a) LEBT chopper, 36 watts; (b) MEBT chopper, 215 watts; (c) linac dump, 20 watts; (d) HEBT transverse collimators, 600 watts; (e) HEBT momentum collimator, 2000 watts; (f) injection dump, 80000 watts; (g) ring collimators, 3800 watts, and (h) RTBT collimators, 20 watts [28].

3.2 Uncontrolled Beam Losses: In spite of the specific built-in measures for prevention, localization and reduction of beam loss, we expect some uncontrolled losses, and these should be below 1W/m. Uncontrolled losses are usually caused by (1) interruptions in the focusing periodicity caused by linac structure, lattice and frequency; (2) limited acceptance-to-emittance ratio; (3) errors including misalignments, magnetic field, and rf phase & amplitude; (4) beam transverse position and energy jitter coming from the linac due to dynamic changes such as mechanical vibrations (drift tube oscillation, microphonics etc), temperature change; (5) phenomena associated with beam transients such as beam loading, Lorentz detuning, droop in beam current, rf amplitude etc; (6) H^- stripping due to background gas and Lorentz forces in the magnetic field; (7) space charge effects in the linac causing parametric & envelope resonance and anisotropy, and in the ring responsible for instability enhancement [29]; (8)

instabilities such as resistive impedance and electron cloud [30,32]; (9) accidental loss due to system malfunctions.

The measured RFQ transmission is more than 80%. The 20% lost beam in the RFQ will not activate the area because of its low energy (< 2.5 MeV) and fulfills the requirements for hands-on maintenance. Simulations show some losses in the linac at the transitions of transverse focusing and RF frequency. Scaling from other linacs like LANSCE, losses in the warm linac should be below 1Watt/m. Losses in the superconducting linac should be negligible due to its larger bore radius and better vacuum [28]. The calculations showed the stripping losses would contribute a significant fraction of the loss limit of 1Watt/m along the linac, especially in the low energy range where the stripping cross-sections are larger. Most of the uncontrolled beam losses in the HEBT will be due to H^- stripping in background gas $\sim 1.6 \times 10^{-7}$/m. The Lorentz stripping will be of order 10^{-8}/meter. Estimates of the beam loss in the injection area are (a) 3.7×10^{-5} due to nuclear scattering of beam in the charge exchange carbon foil and (b) 1.3×10^{-7}: due to Lorentz stripping in the injection chicane magnet INJB2. Simulations shows spurious losses all around the ring are 1.0×10^{-4} arising from the inefficiency of the ring collimator system. The expected losses along the RTBT line during normal operation are negligible [28].

4. Summary

The Spallation Neutron Source facility is designed for 1.4 MW beam power, an order of magnitude higher than any presently operating accelerator based neutron power source. The facility is designed for hands-on maintenance, and is also designed to accommodate a future upgrade to reach beam energy up to 1.3 GeV, a beam power higher than 2 MW, and a second neutron target [31].

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5 References

[1] N. Holtkamp, Proceedings of the 2002 European Particle Accelerator Conference, p 164.
[2] 7th ICFA Mini-Workshop on High Intensity, High Brightness Beams, Sept 1999.
[3] K. Saadatmand et al, Proceeding of the 1993 Particle Accelerator Conference, p 2986.
[4] J. Alessi et al, Proceeding of the 1998 Linear Accelerator Conference, p 196.
[5] D. Raparia, et al, Review of Scientific Instruments 65: 5 (MAY 1994), p 1778.
[6] J. Staples, et al, Proceeding of the 1998 Linear Accelerator Conference, p 176.
[7] J. Staples, et al, Proceeding of the 1999 Particle Accelerator Conference, p 1961.
[8] A. Ratti, et al, Proceeding of the 1998 Linear Accelerator Conference, p 276.
[9] D. Raparia, Proceeding of the 1995 Particle Accelerator Conference, p 3385.
[10] J. Staples, et al, Proceeding of the 2000 Linear Accelerator Conference, p 250.
[11] D. Jeon, et al, Proceeding of the 2002 Linear Accelerator Conference, to be published.
[12] J. Stovall, et al, Proceeding of the 2001 Particle Accelerator Conference, p 446.
[13] K. R. Crandall, et al, Proceeding of the 1992 Linear Accelerator Conference, 405.
[14] I. Hofmann, et al, Proceeding of the 2001 Particle Accelerator Conference, p 2902.
[15] J. Stovall, et al, Proceeding of the 2002 Linear Accelerator Conference, p 605.
[16] D. Raparia, et al, Proceeding of the 1997 Particle Accelerator Conference, p 1297.
[17] N. Catalan-Lasheras, et al, Proceeding of the 2001 Particle Accelerator Conference, p 3263.
[18] Y. Y. Lee, et al, Proceeding of the 2002 Linear Accelerator Conference, to be published.
[19] J. Wei, et al, Phys. Rev. ST-AB 3, 080101 (2000).
[20] J. Wei, et al, Proceeding of the 2001 Particle Accelerator Conference, p 2560.
[21] N. Catalan-Lasheras, et al, Phys. Rev. ST Accel. Beams 4, 010101 (2001).
[22] T. Abell, et al, Proceeding of the 2000 European Particle Accelerator Conference, p 2107.
[23] J. Beebe Wang, Proceeding of the 2001 Particle Accelerator Conference, p 1508.
[24] D. Raparia, BNL/SNS Tech. Note No 058, February 1999.
[25] S. Cousineau, et al, Proceeding of the 2001 Particle Accelerator Conference, p 1723.
[26] D. Raparia, et al, Proceeding of the 1999 Particle Accelerator Conference, p 1297.
[27] D. Raparia, et al, submitted to Particle Accelerator Conference 2003.
[28] N. Catalan-Lasheras, et al, Proceeding of the 2002 European Particle Accelerator Conference, p 1013.
[29] A. Fedotov, submitted to Particle Accelerator Conference 2003.
[30] M. Blaskeiwicz, submitted to Particle Accelerator Conference 2003.
[31] W. T. Weng, et al, Proceeding of the 2002 European Particle Accelerator Conference, p 1070.
[32] J. Wei, et al, submitted to Particle Accelerator Conference 2003.
[33] P. Wanderer, et al, submitted to Particle Accelerator Conference 2003.
[34] P. He, et al, submitted to Particle Accelerator Conference 2003.